KNOWLEDGE BASED SYSTEM FOR DIAGNOSIS OF ROTATING MACHINERY

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CERTIFICATE

This is to certify that the work "Knowledge Based System for Diagnosis of Rotating Machinery", by Vivek Ranjan Nema has been carried out under my supervision and it has not been submitted elsewhere for the award of a degree.

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ABSTRACT

The present work concerns itself with development of a software shell for fault diagnosis in rotating machinery installations. Expert system methodology of creating a knowledge-base and using inferencing techniques similar to that of a human expert are employed in developing the shell. Mathematical tools of Baye's Conditional Probability Analysis and Influence Coefficient Matrix are used for the inferencing.

The shell has been developed in GCLISP. It is also referred to as kno w ledge-based system to indicate the fact it uses a stored knowledge-base (in the form of matrix of conditional probabilities) to decide on the order of the likely causes of vibration. The software lists the probable defects of the machinery in their order of likelihood of presence in the installation. The use of the shell has also been illustrated for the case of a High Speed Turbomachine in a Petroleum Plant.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Supervision of machinery health is a subject of increased importance in the course of progressive automation. Machinery condition monitoring is essential in order to anticipate problems in time in order to prevent complete failure. It serves the important task of ensuring operation within design constraints. Secondly, condition monitoring warns of changing or deteriorating conditions to prevent equipment failure and costly secondary damage. Early warning about the presence of a problem can be obtained while the problem is still localized. Thirdly condition monitoring provides an accurate description of machine condition in order to determine the frequency and extent of maintenance and overhauls without jeopardizing the integrity of equipment in satisfactory condition by disassembling it for visual inspection. In addition it warns of an impeding failure that could be hazardous to personnel and adjacent equipment.

Vibration analysis has proved to be a powerful tool for analysis of failure in rotating machinery. Vibration analysis with appropriate instrumentation can provide reliable knowledge of machine condition and allows relatively inexpensive repair on a prescheduled controlled basis in comparison to catastrophic failures whose repair may cost many more times. Condition monitoring based on vibration signature analysis is a custom built system for effective product quality assurance or machinery fault diagnosis. It normally includes the following-

1. Listing of all critical locations of a machine for monitoring the signatures.
2. Identifying the vibration generating mechanisms and establishing acceptance level of machinery vibration and its spectral characteristics.
3. Determining the machine condition and normal vibration level and spectrum.
4. Selecting the interval for periodic vibration checks.
5. Starting from a sample data recording system which correlates the vibration signatures with machine condition.

Advances in data acquisition techniques and the developments in the areas of knowledge achieving, processing and programming offer potential for application of automated strategies for machinery process supervision which would permit early detection of faults than is possible through conventional limits and trend checks.

Meaningful and more efficient strategies for condition monitoring of rotating machinery are a pressing need , due to increasing demands on reliability and safety, especially for power generating systems.

1.1 Literature survey

Diagnostic systems generally use a multitude of observations for diagnosis and use diagnostic models to define the relationship of the measured signals to individual faults (Pau, 1975). Diagnostic models are either mechanistic or empirical. Mechanistic models which are derived from the physics of the process are dynamic state models and

assume complete knowledge of the measurement characteristics (Willsky, 1976 ; Ishermann, 1984). These models have an analytic foundation, therefore they can take advantage of the various parametric identification techniques for diagnosis (Stein and Park 1988 ; Ono et al , 1987).

Lipsom has presented a general discussion on the failure of machine parts. Elaborate results of experimentation on unbalance producing phenomena and balancing by statistical and probabilistic methods have been presented. Rao (1991) has presented a documentation of the dynamic performance of a machine due to rotating unbalance, fluid film bearings , asymmetric cross sections of the shaft etc. Most mechanical systems are, however too complex for such mechanistic modeling and the approach has limited application.

Empirical models on the other hand are developed from heuristically defined and / or experimentally established fault signatures. Since these models do not require detailed understanding of the process, they gain wider acceptance for performance monitoring of complex systems (Collacott, 1976 ; Cempel, 1988 ; Lyon and Dejong, 1984 ; Gilmore and Gingher, 1986).

Ignezio (1969) , Alty (1989) , Rich (1990) present the expert system building tools in their works. Hill and Beines (1984) pointed out the utility of an expert system for maintenance personnel and suggested the development of one using Sohre's database (1968). An expert system for machine monitoring is described by Reilly and MacPhail (1991). Lewis and Seth (1990) also described a rule based expert

system for vibration oriented diagnosis of turbomachinery for fault identification and predict maintenance in PC based Prolog environment. Typically the experts knowledge is represented by if - then rules and the observations are contained in a fact-base. An inference engine selects the rules to apply by matching the conditional side of the rules to the observations.

1.2 Present Study

The present study concerns itself with development of diagnostic shell for rotating machinery with special reference to power plants. In the context of power plants very significant experimental investigations have been carried out by Sohre (1968). A vast amount of data, for various kinds of faults in the rotating machinery and the associated symptoms in vibration signatures have been generated by Sohre for a real life power plant. An attempt has been made in the present study to organize Sohre's data in the form of a knowledge base. Automation of the decision making process by relating symptoms to the cause through development of inference engines is carried out. Two separate inferencing techniques have been developed - one based on probabilistic reasoning based on Baye's Rule and the other based on Multi - Valued Influence Matrix (MVIM) approach suggested by Danai and Chin (1991), which in preference to probabilistic approach tries to match the symptom vectors from the test to those related to a specific fault, thereby achieving a reduction in decision making time-lag in comparison to a probabilistic approach.

A brief review of the commonly occurring faults in rotating machinery is presented in Chapter 2 while Chapter 3 reviews expert systems programming procedures. Chapter 4 presents the modeling of the problem and shell structure. Chapter 5 presents a case study on a power plant evaluation and Chapter 6 concludes with a discussion on scope for future work.

CHAPTER 2

PROBLEMS IN ROTATING MACHINERY

Rotating machinery are employed in various industrial installations such as steam and gas turbines , turbogenerators , internal combustion engines , reciprocating and centrifugal compressors etc. The complexity of the dynamics of these machinery depends on the size as well as the operating speed. On account of the ever increasing demand for power and high speed transportation , the rotating machinery is being made increasingly light and flexible, thereby increasing the dynamics complexities. Any fault in the system results in corresponding changes in the behavior of the system and vibration signatures of the machine become important indicators of the health of the system Typical rotating machinery installations involve mechanical elements like rigid or flexible shafts carrying one or more discs with bladed components. The arrangement may be supported in rolling element or fluid film bearings with associated components like couplings, seals, gear-boxes, pulleys etc. The installation is carried by pedestals which are mounted on foundations. The commonly occurring faults in rotating machinery are cracks on shafts, loss of blades on discs, deteriorating balance, bows of shafting, shaft misalignment, oil film whirls, gear misalignment and damage, bearing eccentricities, coupling inaccuracies and damage, pedestal and foundation cracks etc.

2.1 Classification of Rotating Machinery Vibration Causes

The various kinds of rotating machinery faults become the cause for changes in the dynamics of the system. The changes in the system dynamics are reflected in the vibration signatures of the machine. The causes of vibration in the rotating machines are broadly classified as follows :

(1) Unbalance

Unbalances in machinery arise due to eccentricities between geometrical and mass centers in components. During rotation these unbalances generate large centrifugal forces in the machine which cause vibrations at the rotor speed i.e. one per revolution. Some specific unbalances created during the running of the machine give rise to additional characteristics, also Fig 2.1 lists causes of unbalance and the frequency of vibration they cause.

(2) Distortion (Casing and Foundation)

Casing and Foundation distortion cause vibration in an indirect way either by generating misalignment between driver and driven machine or by causing internal rub or uneven bearing contact. This in turn transmits forces to the rotor, inducing it to generate forces of its own such as unbalance and a wide variety of oil film and friction induced forces. Another possibility is that the loads on casing supports shift and can set off a series of resonance problems. Piping forces and foundation distortion often cause this type of difficulty.

Cause of unbalance	Observable sign	Frequency of vibration
Disk or component eccentric on shaft	Detectable runout on slow rotation	One / rev
Dimensional inaccuracies	Measurable lack of symmetry	One / rev
Eccentric machining or forming inaccuracies	Detectable runout	One / rev
Oblique angled component	Detectable angular runout	One / rev
Bent shaft. Distorted assembly	Detectable runout on slow rotation; heavy vibration during rotation	One / rev
Section of blade or vane broken off	Observable bearing vibration during operation	One / rev
Eccentric accumulation of process dirt on blade	Bearing vibration	One / rev
Differential thermal expansion	Shaft bends & throws c.g. out, Source of heavy vibration	One / rev
Nonhomogeneous component structure, subsurface voids in casting	Rotor machined concentric. Bearing vibration during operation	One / rev
Non-uniform process erosion	Bearing vibration	One / rev
Loose bolt or component slip	Vibration reappears after balancing	One / rev
Trapped fluid inside rotor	Vibration reappears after balancing	One / rev
Ball-bearing wear	Bearing vibration	One, two or higher / rev

Table 2.1 Typical causes of rotor unbalance

(3) Misalignment

Coupling misalignment causes friction or deflection forces in the coupling and this in turn causes the rotor and bearing system to deflect and to amplify these forces possibly creating secondary phenomenon such as harmonic resonance which can become severe. Frequencies are characteristically 2 x Running Frequency (RF) for gear couplings, but 1 x RF is also often observed.

(4) Bending Criticals and Resonance

A rotor runs into resonance when the rotational speed is equal to its lateral (bending) vibration frequency. Bending critical speeds can be easily detected by synchronous whirl conditions and fairly large amplitude at the rotor speed. The critical speed region occurs over a fairly large range in the case of oil film bearings and is often accompanied by backward whirl. Resonance of the structures, support and auxiliaries cause fairly large amplitudes of vibration at the rotor speed.

(5) Asymmetric shaft

The response of the asymmetric shaft has several harmonics and the frequencies observed are 1 X rev, 2 X rev, 3 X rev and sometimes even harmonics, if the symmetry is predominant.

(6) Torsionals

Torsional criticals in machinery are detected by torsional vibration measuring instruments. Unless there is a gear box in the transmission unit, it is difficult to detect these criticals

by vibrometers or accelerometers used for conventional non-angular vibratory measurements Torsional criticals are predominant in reciprocating machinery, as there is large excitation torque . In rotating machinery , they are not easily excited , unless there is a disturbance arising out of gear transmission units. Reciprocating machines have several criticals, some of them major, between the starting and operating speeds. In pure turbomachinery torsional excitation is normally very weak and inconsequential.

(7) Oil Film Whirl

Instabilities in rotors can also arise due to oil film forces in the bearings. This is self excited type of motion and is called oil whirl or oil whip. The frequency of response at the onset of the whirl is always a little less than 1/2 rev , in the region of 0.4 to 0.5 X rev.

(8) Mechanical Looseness

Looseness of components is the likely cause of most number of problems. Loose rotor components such as disks, sleeves, thrust collars etc. cause internal friction problems. Internal friction is a destabilising factor. The frequency of vibration is always the rotor critical speed and hence easy to detect. Mechanical loose components like bolts, give rise to 1 X rev and harmonic frequency signals due to secondary phenomena. The amplitude and phase continually change.Loose assembly of bearings give rise to subharmonic response and the typical frequency response is 1/2 X rev and 1/3 X rev.

Table 2.2 summarizes some of the common faults in the rotating machinery along with the resultant frequencies and directions of dominant vibrations.

2.2 Comments

The large variety of components on rotating machinery installations, with their complex dynamic interrelationships and the possibilities of occurrence of different kinds of faults, make health monitoring of such a difficult task. Conventional manual trend checking techniques are obviously inadequate which has led to increased activity in development of automated diagnosis and prognosis procedures for rotating machinery installations.

	Fault	Dominant Frequency	Direct
1	Rotating unbalance	Rotating speed , n	R
2	Reciprocating unbalance	n , 2n , 3n n/2 , n/3 etc.	R
3	Bent shaft or coupling	n	R, B
4	Misalignment	2n , sometimes n , 3n , 4n	R, A B
5	Mechanical looseness	n , 2n , 3n	R, A B
6	Loose Rotor components	Rotor critical speed and higher harmonics	R B
7	Loose journal bearing	n/2 , n/3	R, B
8	Oil film whirl	0.4 to 0.5 and harmonics	R B
9	Damaged hydrdynamic bearing	Change in higher frequencies	R B
10	Assymetric shaft	n , 2n , 3n	R, B

Abbreviations

R	Radial
A	Axial
B	Bearing housing

Table 2.2 Vibration Characteristics of Some Machine Parts

CHAPTER 3

EXPERT SYSTEM PROGRAMMING

Expert Systems are 'intelligent' computer programs that exhibit within a specific domain a degree of expertise in problem solving that is comparable to a human expert. Here intelligent refers to Artificial intelligence (AI). Expert systems are considered to be one of the most successful application of AI. Based on its function an expert system can be classified as being of the following type :

1. Prediction System : Infers likely consequences from given situation .(eg. Expert system for weather-forecasting)
2. Diagnostic System : Infers system malfunction from observed data / phenomenon (eg. the well-known Expert system for diagnosis of blood infection : MYCIN).
3. Design system : Solves or assists to solve design problems and develop configuration of objects to meet specific design constraints of the problem (eg. PROCON for providing assistance for design of Mechanical systems.).
4. Planning Systems : Designs a sequence of actions based on requirements and criteria (eg. Expert system for process planning in Arc Welding).
5. Speech Recognition : Tries to interpret spoken input (eg. HEARSAY I and II).
6. Monitoring System : Compares the system performance with model of expected performance (eg Process Intelligent Control , PICON for monitoring a plant operation control system).

The motivation for building expert system consists of one or more of the following :

1. to act as substitute of the costly human expertise
2. to formalize and standardize expert knowledge
3. to integrate diverse source of knowledge about a problem domain and its solution methods.

3.1 Organs of Expert Systems

Some important terms associated with knowledge based systems are as follows :

* Knowledge base . - The knowledge base is the most important part of an expert system . It is in the form of facts and rules. The facts are termed deep knowledge. The rules are simply the heuristics which are also termed shallow knowledge.

* Inference Engine - The inference engine serves as the inference and the control mechanism for the expert system and as such is an essential part of the expert system. It interacts with the user and uses the facts in the knowledge base according to the rules contained it (Fig 3.1). Like the knowledge base the inference engine also contains rules and facts. But while the rules and facts of the knowledge-base pertain to the specific domain of expertise, the rules and facts of the inference engine concern more with the general control and search strategy employed by the expert system.

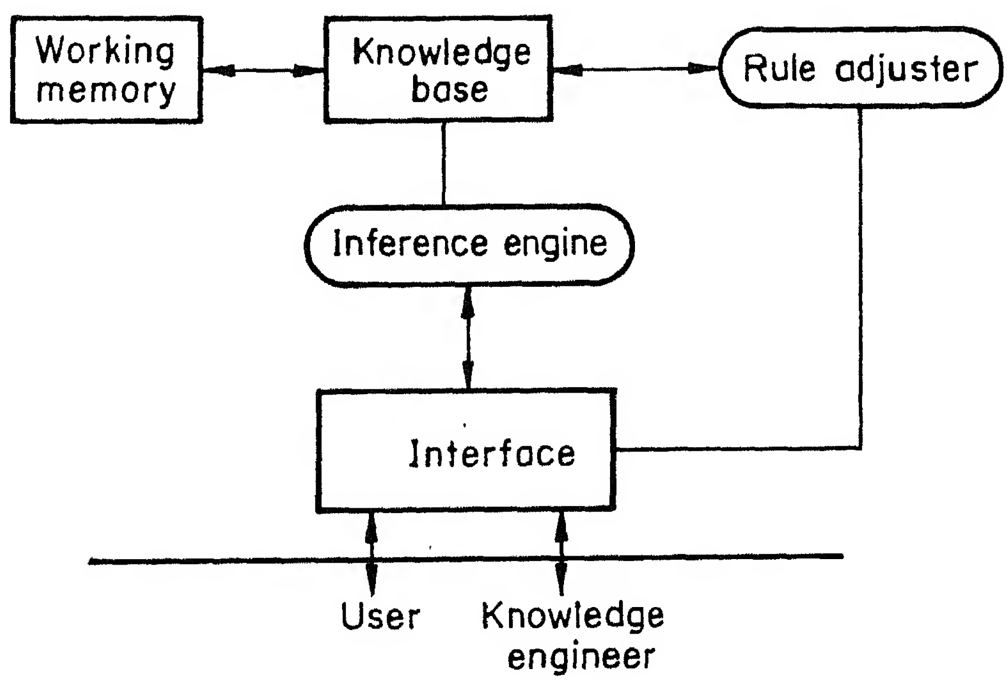

Fig.3.1 A generic expert system

* Expert System Shells - It is a commercially available expert system architecture and it has the main components of the expert system except for the knowledge base. The knowledge-base is inserted into it to make a complete expert system. The use of shells thus frees the knowledge engineer from the need to repeatedly develop all the supporting elements of an expert system and thus to focus his or her attention on the development of the knowledge-base . Some well known commercial shells are Rulemaster, CxSYS, EXPERT etc.

* Working Memory - The contents of the working memory consist of facts. However unlike the facts within the knowledge base these facts are those that have been determined for the specific problem under consideration during the consultation session. More specifically the results of the inference process are new facts and these facts are stored in the working memory.

* Rule Adjuster - This serves as a rule editor, i.e., it enters the rules into the knowledge- base during the development phase of an expert system. It mainly concerns with expert systems built on expert system shells.

* Knowledge Representation - The knowledge that is contained within an expert system consists of the following -

  A priori knowledge - the facts and rules that are known about a specific domain prior to any consultation session with the expert system.

  Inferred knowledge - the facts and rules concerning a specific

case that are derived during, and at the conclusion of a consultation with the expert system. Rules are generated during a consultation with an expert system only if the expert system is capable of learning. In general inferred knowledge consists simply of new facts, or conclusions.

The major concerns of knowledge representation are the following

To provide a format compatible with the computer.

To maintain as close as possible a correspondence between this format and the actual rules and facts.

To establish a representation that can be easily addressed, retrieved, modified and updated.

Some common modes of knowledge-representation are as follows

<u>Object-attribute-value Triplets (OAV Triplets)</u>

OAV triplets provide a particularly convenient way in which to represent certain facts within a knowledge base and may be extended to provide the basis for the representation of heuristic rules. Using airplane as an example some of the attributes include the following :

- o Number of engines
- o Type of engine
- o Type of wing design

Values may be symbolic or numeric. And in the above example the values may be as given below

- o Number of engines = *4*
- o Type of engine = *jet*
- o Wing design = *swept back*

Semantic Networks

A semantic network may be thought of as a network that is composed of multiple OAV Triplets in network form. However rather than pertaining to just one attribute for a single object, semantic network can be used to represent several objects and several attributes per object.

Frames

This is a particularly robust way of representing knowledge. A frame contains an object plus slots for any and all information related to the object. The contents of such slots are attributes and attribute values. However in addition to storing values for each attribute, slots may contain default values, pointers to other frames, and sets of rules and procedures that maybe implemented. Thus semantic networks may be thought of as a subset of the concept of frames. Frames are useful for the design of large-scale, complex expert systems - particularly those involving a large amount of a priori facts and multiple objects.

Representation via Logic Statements

The most common form of logic is propositional logic. A proposition in turn is a boolean statement , it may either be true or false. Propositions may either be linked together with various operators called logical connectives such as AND, OR, NOT and EQUIVALENT. Linked propositions are called compound statements.

Predicate Calculus is simply an extension of propositional logic. The fundamentals of predicate calculus are the object and the predicate. A predicate is simply a statement about the object or a relationship that the object possesses. Some examples of the use of predicate calculus are as follows :

- o Tail(dog) , which is read as 'a dog has a tail'
- o Brother(Ram, Shyam) , which is read as 'Ram is Shyam's brother'.

Representation via Rule-Based Systems

This is the most popular mode of knowledge representation at least at this time. The rules are of if-then type or production rules.

Some of the important properties of these type of rules are as follows :

- o Name (name of the rule)
- o Premise (the if portion of the rule)
- o Intermediate conclusion (the then portion of the rule)
- o Conclusion (the then portion of the rule)
- o Notes (notes associated with the rule)
- o Confidence factors (a measure of confidence in the rule's conclusion
- o Chaining Preference (the normal or default mode of search by th rule

3.2 Comments

Few expert systems involve all these organs together.The type of knowledge base and inference engine depends on the problem concerned. The present expert shell uses lists of lists to represent the matrix of probabilities because the multiple array data structure is not available in GCLISP.It comprises of a Knowledge Base, a Logic Analyzer, a Network and Inference Engines.

CHAPTER 4

DIAGNOSTIC SHELL

The diagnostic shell developed during the present study is based on empirical data by Sohre (1968) and available heuristic knowledge. As stated earlier, an empirical model does not necessitate detailed analytic understanding of the process and thus finds greater acceptance in terms of efficiency. Since the knowledge or data in most cases may be incomplete or uncertain, empirical models employ probabilistic reasoning techniques such as Baye's Rule, Fuzzy Logic, Dempster-Shafer Calculus etc.The present uses shell Baye's rule for probabilistic reasoning. In addition an Influence Matrix Approach, Danai and Chin (1991) for reasoning is also presented in this study.

4.1 Shell Structure

The diagnostic shell developed is described in Fig 4.1. The shell comprises of a Knowledge Base which is organized in the form of frames. A Logic Analyzer is appended to each frame for probabilisation reasoning within the frame. The Logic Analyzers of the various frames are networked for overall probabilistic reasoning. User interface is available on initiating the shell whereby the observed symptoms can be logged in. At the network level user interface is once again provided to choose to an appropriate inference engine for diagnosis.

The various components of the shell developed are described in the following.

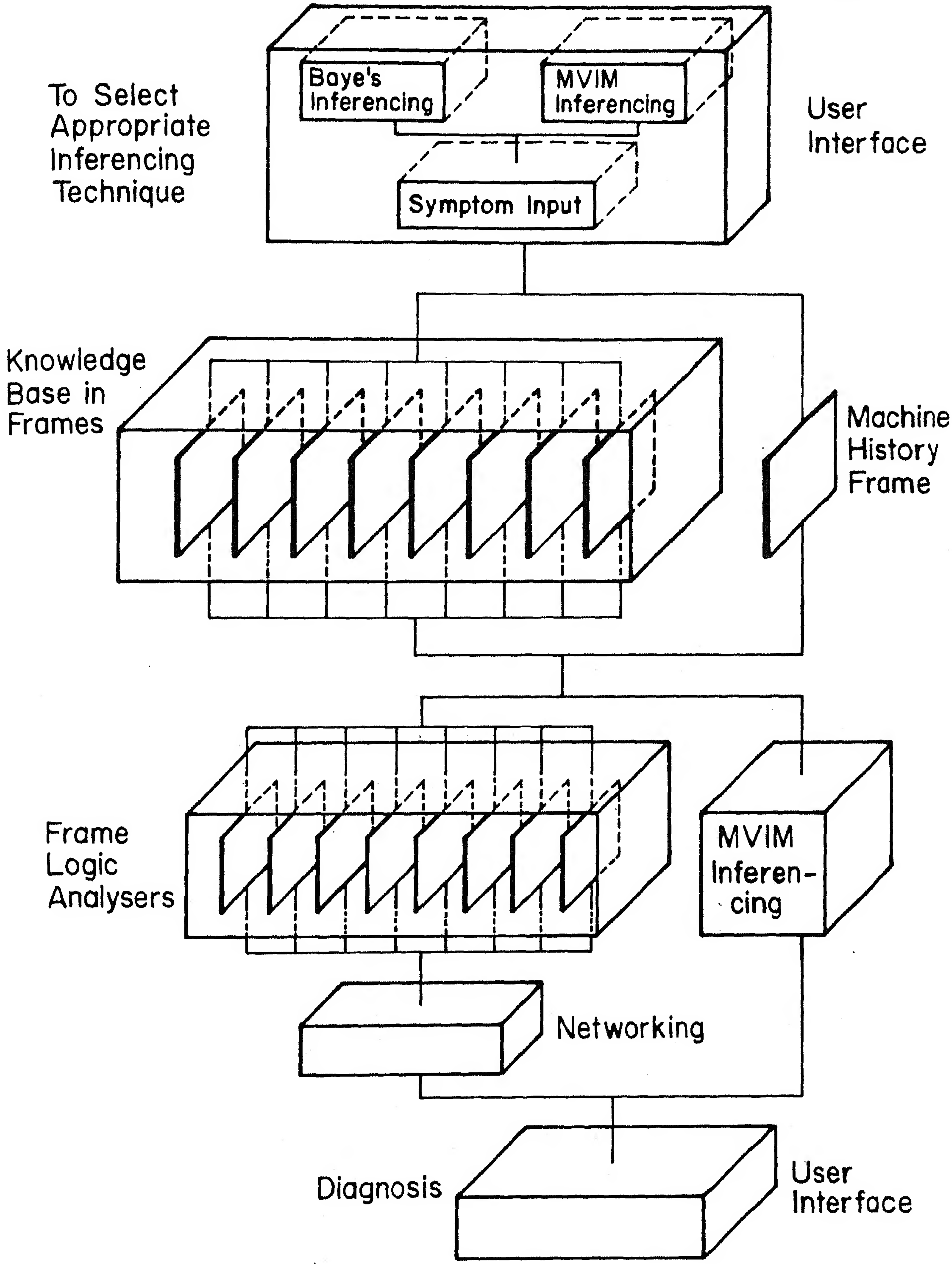

Fig. 4.1 Shell Structure

4.2 Knowledge Frames

The knowledge base is organized in the form of 'frames'. A frame, in the shell developed in this endeavor, is a collection of probabilistic data relating 'causes' and 'symptoms' for a particular 'monitoring parameter'. For example the frame in Fig 4.2 would contain the probabilistic data on the occurrence of particular 'symptoms' namely vibrations at Rotor Frequency , Oil Whirl Frequency, 1 X Running Frequency, 2 X Running Frequency due to 'causes' of Unbalance , Casing Distortion, Bearing Eccentricities. The symptom in the Fig 4.2 are all related to the monitoring parameter of 'Frequency of Predominant Vibration'.

CAUSES OF VIBRATION ↓	SYMPTOM →	ROTOR OR STATOR RESONANT FREQ	40-50% of OIL WHIRL FREQ.	50-100%	1 X RUNNING FREQ.	2 X R. F.	HIGHER MULTI-PLE
UNBALANCE		0.05	0.0	0.0	0.2	0.05	0.05
CASING DISTORTION		0.02	0.04	0.02	0.6	0 2	0 1
BRG-ECCENTRICITY		0.6	0.0	0.0	0.4	0.6	0 0

Fig 4.2 Cause - symptom frame for monitoring parameter 'Predominant Frequency'

Fig 4.3 shows a frame for the same set of 'causes' but 'symptoms' for monitoring parameter 'Direction of Predominant Amplitude'.

CAUSES OF VIBRATION ↓	SYMPTOM →	VERTICAL	HORIZ.	AXIAL
UNBALANCE		0.4	0.5	0.1
CASING DISTORTION		0.4	0.5	0.1
BRG-ECCENTRICITY		0.4	0.5	0.1

Fig 4.3 Cause - symptom frame for monitoring parameter 'Location of Predominant Amplitude'

In the shell developed the 'frames' incorporate the following 'causes' (causes are the rows in frames) :

(1) Unbalance

(2) Permanent Bow

(3) Temporary Bow

(4) Casting Distortion

(5) Foundation Distortion

(6) Leaf Cut

(7) Rotor Rub

(8) Misalignment

(9) Piping Losses

(10) Bearing Eccentricity

(11) Bearing Damage

(12) Excited Vibration

(13) Unequal Stiffnesses

(14) Thrust Bearing Damage

(15) Loose Assembly of rotor

(16) Gear Inaccuracy

(17) Coupling Inaccuracy

(18) Aerodynamic Excitation

(19) Rotor System Critical

(20) Coupling-critical

(21) Overhang-critical

(22) Structural Resonance of Casting

(23) Pressure Pulsations

(24) Electrically Excited Vibrations

(25) Vibration Transmission

(26) Oil Seal Induced Vibration

The frame incorporates seven frames in its knowledge base. Each frame pertains to a specific 'monitoring parameter'. The seven monitoring parameters along with the associated symptoms (which form the columns in the frames) are :

(1) Predominant Frequencies

Rotor or stator resonant frequency

40 - 50 % oil whirl frequency

50 - 100% oil whirl frequency

Equal to running frequency

Twice running frequency

Higher multiple of running frequency

Half of running frequency

Quarter of running frequency

Lower multiple of running frequency

An odd frequency

Very high frequency

(2) Direction of Predominant Amplitude

Vertical

Horizontal

Axial

(3) Location of Predominant Amplitude

Shaft

Bearings

Casting

Foundation

Piping

Coupling

(4) <u>Amplitude Response to Speed Variation</u>

(<u>Speed Coming Up</u>)

Stays same

Increases

Decreases

Peaks

Comes suddenly

Drops out suddenly

(5) <u>Amplitude Response to Speed Variation</u>

(<u>Speed Slowing Down</u>)

Stays same

Increases

Decreases

Comes suddenly

Drops out suddenly

(6) <u>Predominant Sound During Vibration Test Run</u>

Low frequency rumble

Hum

Beat (i e comes and goes periodically)

High pitched whine

Very high loud scream

Very high squeal

Ultrasonic (Measured with sound analyzer)

(7) <u>Responses for the effect of operating conditions</u>

Comes in or goes out at

- No effect
- Full load in
- Full load out
- No load in
- No load out
- Part load in
- Part load out
- Start up only
- After load dump or surge
- When other machine starts or shuts down

(8) <u>Known operational evidence</u>

- Seals rubbed
- Shaft bent
- Thrust bearing damaged
- Bearings wiped out
- Bearings fatigued
- Bearings babbit squeezed out
- Case distorted or cracked
- Misalignment
- Coupling burned or pitted
- Gear teeth broken or pitted
- Gear teeth marked on the back side
- Shaft cracked or broken
- Gailing or fretting marks under disks or hubs
- Coupling bolts loose

Foundation cracked

Soleplate loose or rusted

Sliding surfaces binding

Thermal expansion restricted

Fluid marks on the internals

Rotor components eroded

Solid accumulated on vanes and rotor

Salt deposited on internal

Flanges leaking

Seals leaking

(9) <u>The History of Machine</u>

Initial start-up

Start-up during the first year

Start-up after one year but before ten years

Start-up after ten years

4.3 Probabilistic Logic Analyzer Using Baye's Rule

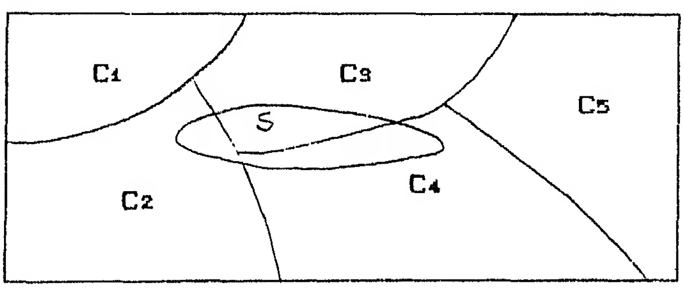

Fig 4.4 Conditional Appearance Symptom

Let S_i represent the occurrence of the ith symptom which may be caused by any of the independent causes C_1, C_2, C_3 etc.

If a symptom S is observed then the object of the Logic Analyzer is to predict the probability $P (C_k / S)$ of the existence of the cause C_k given the observation of the symptom S.

With reference to Fig 4.3 the probability element p_{ij} in any knowledge frame can be seen as the percentage of cause C_j overlapped by symptom S_i.

Let S be the symptom of 'Foundation Vibration' in the frame concerning 'Location of Predominant Amplitude', then this fact can also be represented as

S = (Not Shaft) and (Not Bearing) and (Not casting) and (Foundation) and (Not piping) and (Not coupling)

or

$$S = (\neg S_1) \cap (\neg S_2) \cap (\neg S_3) \cap (S_4) \cap (\neg S_5) \cap (\neg S_6) \quad (1)$$

The knowledge frames consist of elements p_{ij} = the probability of occurrence symptom S_i when fault C_k is present in the machinery.

If the appearance of symptoms is independent of each other, then

$$P (S_i \cap S_k) = P (S_i) * P (S_k) \quad (2)$$

Application of (2) in (1) gives

$$P (S / C_k) = P (\neg S_1 / C_k) * P (\neg S_2 /C_k) * P(\neg S_3 /C_k) * P(S_4 /C_k) * P (\neg S_5 / C_k) * P (\neg S_6 / C_k) \quad (3)$$

Since $P (\neg S_i / C_k) = 1 - P (S_i / C_k)$ (4)

Using the available data in the knowledge frame $P (S / C_k)$ can be evaluated.

Defining the total probability, P(S), of occurrence of a symptom S as

$$P(S) = \sum^{k} P(S \cup C_k)$$

$$= \sum^{k} P(S / C_k) * P(C_k) \qquad (5)$$

Where $P(C_k)$ is the probability of the presence of a cause C_k. The probability $P(C_k)$ is picked from the Machine History Knowledge Frame which is constructed as shown in Fig 4.5.

CAUSES OF VIBRATION ↓	SYMPTOM →	INITIAL START-UP	FIRST YEAR.	UNDER TEN YEARS	OVER TEN YEARS
UNBALANCE		1.0	0.0	0.0	0.0
PERMANENT BOW		0.99	0.0	0.99	0.94
TEMPORARY BOW		0.67	0.99	0.0	0.0

Fig 4.5 Machine History Knowledge Frame

Using the definition of conditional probability

$$P(C_k / S) = P(C_k \cap S) / P(S) \qquad (6)$$

Since

$$P(S / C_k) = P(S \cap C_k) / P(C_k)$$

$$\text{or } P(S \cap C_k) = P(S / C_k) * P(C_k) \qquad (7)$$

As $P(S \cap C_k) = P(S \cap C_k)$, (6) gives

$$P(C_k / S) = P(S / C_k) * P(C_k) / P(S) \qquad (8)$$

Employing (5) in (8) the conditional probability of the presence of cause C_k given the observation of symptom S can be written as

$$P(C_k / S) = \frac{P(S / C_k) * P(C_k)}{\sum^{k} P(S / C_k) * P(C_k)} \qquad (9)$$

Equation (9) is known as Baye's Rule for Conditional Probability.

4.4 Networking of Frames

After obtaining the conditional probability of the existence of a cause given the observation of a particular symptom for each of monitoring parameter, the probability values for all the frames are to be networked to give an overall conditional probability of the existence of a cause for a given set of observations. The networking scheme is described in the following.

The 'Odds' of the presence of a cause is defined as the ratio of the probabilities of occurrence of the cause to its non-occurrence. For example for an event X with the probability of occurrence as P (X) the odds are defined as

$$O(X) = P(X) / [1 - P(X)] \quad (10)$$

Odds Likelihood Ratio of the existence of a cause C_k is defined as

$$\lambda = P(S / C_k) / P(S / \neg C_k) \quad (11)$$

Simplified the above gives

$$\lambda = O(C_k / S) / O(C_k) \quad (12)$$

The eight monitoring parameters are independent of each other. Therefore the overall likelihood ratio (λ) is

$$\lambda_E = \lambda_1 * \lambda_2 * \lambda_3 * \lambda_4 * \lambda_5 * \lambda_6 * \lambda_7 * \lambda_8 \quad (13)$$

This effective value λ_E can be used to calculate the final probability of the cause

$$\lambda_E = O(C / S) / O(C) \quad (14)$$

Where S is the global set of symptom observed pertaining to the

various knowledge frames.

Therefore

$$O(C_k/S) = \lambda_E * O(C_k) \qquad (15)$$

From this $P(C_k/S)$ can be calculated as follows

$$P(C_k/S) = O(C_k/S) / [1 + O(C_k/S)] \qquad (16)$$

Thus $P(C_k/S)$can be calculated for each of the defects C_1, C_2, C_3, C_4 etc and from these the defects with higher probabilities can be short listed.

4.5 MVIM Method

An alternative inference engine based on Multi Valued Influence Matrix diagnostic reasoning is also built into the shell. The MVIM method involves matching the vector of observed symptoms against vector of symptoms pertaining to a particular cause. The inference based on MVIM reasoning is more suitable in cases when data in a particular knowledge frame is uncertain or doubtful and no data entries are made in the frame grid. The absence of the would be taken zero probability leading to erroneous ordering of the causes. The MVIM method works across the frames and ignore the absence of data.

As stated diagnostic reasoning in the Multi Valued Influence Matrix method is based on matching the vector of observed symptoms against vector of symptoms pertaining to a particular cause The particular influence vector at the closest angle to the vector of normalized measurement vector is considered to correspond to the occurred fault. Thus every fault C_k may be characterized by its influence vector as

follows

$$V_k = \begin{bmatrix} a_1 \\ a_2 \\ . \\ . \\ . \\ . \\ a_n \end{bmatrix}$$

where a_i = Prob (S_i / C_k)

(Probability that symptom S_i is observed given fault C_k)

thus $0 \leq a_i \leq 1$

Let the observed vector be

$$. \; V = \begin{bmatrix} v_1 \\ v_2 \\ . \\ . \\ . \\ . \\ v_n \end{bmatrix}$$

It is to be noted that Y is a binary vector, so that v_i taking a value 0 or 1 , 1 if ith symptom is observed and 0 if it is not observed.

Since the angle θ between two vectors

$$A = A_1 i + A_2 j + A_3 k$$

$$B = B_1 i + B_2 j + B_3 k$$

is

$$\theta = \text{Inverse cos } (A_1 B_1 + A_2 B_2 + A_3 B_3) / A \, . \, B \qquad (17)$$

The angle between the observed V vectors and the symptom vector V_k of cause C_k can be found out by extending eq.(17) to n dimensions.

As an example consider the symptom vector for the cause unbalance

$$V_k = \begin{bmatrix} 0.9 \\ 0.1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Where 0.6 is the probability that vibration occurs at the shaft.

Let the observed vector of symptom be

$$V = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Therefore

$$Vk = \sqrt{(\,0.9 * 0.9 + 0.1 * 0.1 + 0 + 0 + 0 + 0\,)}$$

$$= \sqrt{0.82}$$

$$= 0.905$$

$$Y = 1$$

$$y = Y$$

thus $\cos\theta = 0.1 * 1 \;/\; 0.905$

$$= 0.1105$$

The cosine of the angle between the each of the cause vector can thus be calculated and the causes which are at lower angular separation to the symptom vector can be short listed.

4.6 Comments

The shell is developed in GCLISP. LISP stands for LISt Processor and GCLISP is abbreviation for Golden Common LISP marketed by Golden Hill Corporation and is a small memory PC based version of LISPUnlike the procedural languages (like Fortran, Cobol, C and Basic) ; Lisp and Prolog are object oriented languages and they are more suited for developing expert systems and AI. While Prolog employs object data and their relationships, emphasizing symbolic processing, LISP is more suited for backward chaining operations.

CHAPTER 5

SHELL USAGE

The usage of the Expert shell is described in this chapter. Diagnosis of an high speed turbomachinery installation is illustrated. The knowledge base is constructed on the basis of the exhaustive data available from Sohre's (1968) work on Petroleum Plants. Employing the various features of LISP programming a question-answer based interface is developed. The output from the shell is obtained in the form of most prominant faults likely to be present in the machinery.

5.1 Knowledge Base Creation

Typical operational knowledge for a High Speed Turbomachinery installation in a Petroleum Plant is organised in the form of 'Frames'. Each frame pertains to a specific monitoring parameter. Table 5.1 to 5.8 describe the organisation of these Cause-Symptom frames for various monitoring parameters . The grid values represent the Cause-Symptom relationships in the form of probability of occurence. The probabilistic knowledge is fed to the computer in the form of list of lists, for example the symptom Location of Predominant Amplitude the list of list would of the following form

```
( (0.9  0.1  0.0  0.0  0.0  0.0)
  (0.9  0.1  0.0  0.0  0.0  0.0)
  (0.9  0.1  0.0  0.0  0.0  0.0)
  (0.9  0.1  0.0  0.0  0.0  0.0)
                .
                .
                .
```

CAUSES OF VIBRATION ↓ / SYMPTOMS →	INITIAL START-UP	FIRST YEAR	UNDER TEN YEARS	OVER TEN YEARS
UNBALANCE	1.0	0.0	0.0	0.0
PERMANENT BOW	0.99	0.0	0.99	0.94
TEMPORARY BOW	0.67	0.99	0.0	0.0
CASING DISTORTION	0.0	0.0	0.5	0.5
FOUNDATION DIS.	0.2	0.2	0.2	0.4
LEAF CUT	0.25	0.25	0.25	0.25
ROTOR RUB	0.67	0.99	0.0	0.0
MISALIGNMENT	0.25	0.25	0.25	0.25
PIPING-LOSSES	0.99	0.17	0.17	0.99
BRG-ECCENTRICITY	1.0	0.0	0.0	0.0
BEARING DAMAGE	0.25	0.25	0.25	0.25
EXCITED-VIBRATION	0.67	0.99	0.0	0.0
UNEQUAL-STIFFNESS	1.0	0.0	0.0	0.0
THRUST-BRG-DAMAGE	0.4	0.2	0.2	0.2
LOOSE-ASSLY-ROTOR	0.2	0.4	0.2	0.2
GEAR INACCURACY	1.0	0.0	0.0	0.0
COUPLING INACCURACY	0.67	0.99	0.0	0.0
AERODYNAMIC EXCIT.	0.4	0.0	0.2	0.4
ROTOR SYSTEM CRITIC	0.67	0.99	0.0	0.0
COUPLING CRITICAL	0.67	0.99	0.0	0.0
OVERHANG CRITICAL	0.67	0.99	0.0	0.0
STRUCTURAL RESONANCE CASTING	0.67	0.99	0	0.0
PRESSURE PULSATIONS	0.2	0.4	0.2	0.2
ELECTRICALLY EXCITED VIBRATION	0.67	0.99	0	0.0
VIBRATION TRANSMIT.	0.5	0.5	0	0
OIL SEAL INDUCED VIBRATION	0	0.4	0.4	0.2

Table 5.1 : Machine History Knowledge Frame

CAUSES OF VIBRATION ↓ / SYMPTOMS →	ROTOR OR STATOR RESONANT FREQ	40-50% OF OIL WHIRL FREQ.	50-100%	1 X RUNNING FREQ.	2 X R.F.	HIGHER MULTI-PLE	1/2 R.F.	1/4 R.F.	LOWER MULT-IPLE	ODD FREQ.	VERY HIGH FREQ.
UNBALANCE	0.05	0.0	0.0	0.9	0.05	0.05	0	0	0	0	0
PERMANENT BOW	0.9	0.0	0.0	0.9	0.05	0.05	0	0	0	0	0
TEMPORARY BOW	0.2	0.0	0.0	0.9	0.05	0.05	0	0	0	0	0
CASING DISTORTION	0.09	0.04	0.09	0.6	0.2	0.1	0	0	0	0	0
FOUNDATION DIS.	0.0	0.2	0.0	0.4	0.9	0.0	0	0	0	0.1	0
LEAF CUT	0.1	0.1	0.1	0.2	0.1	0.1	0	0	0.1	0.1	0.1
ROTOR RUB	0.05	0.1	0.05	0.9	0.1	0.1	0	0	0.1	0.1	0.1
MISALIGNMENT	0.05	0.1	0.0	0.2	0.45	0.1	0	0	0	0	0.1
PIPING-LOSSES	0.5	0.1	0.0	0.9	0.5	0.1	0	0	0	0	0.1
BRG-ECCENTRICITY	0.6	0.0	0.0	0.4	0.6	0.0	0	0	0	0	0
BEARING DAMAGE	0.2	0.0	0.0	0.4	0.2	0.0	0	0	0	0	0.2
EXCITED-VIBRATION	0.2	0.6	0.0	0.0	0.0	0.0	0.1	0.1	0	0	0
UNEQUAL-STIFFNESS	0.8	0.0	0.0	0.8	0.2	0.0	0.0	0.0	0.0	0.0	0.0
THRUST-BRG-DAMAGE	0.5	0.2	0.1	0.05	0.05	0.0	0.0	0.0	0.0	0.0	0.1
LOOSE-ASSLY-ROTOR	0.4	0.4	0.1	0.1	0.1	0.1	0	0	0	0.1	0
GEAR INACCURACY	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.6
COUPLING INACCURACY	0.1	0.2	0.1	0.2	0.9	0.1	0.0	0.0	0.0	0.0	0.8
AERODYNAMIC EXCIT.	0.6	0.2	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.1	0.1
ROTOR SYSTEM CRITIC	1.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
COUPLING CRITICAL	1.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OVERHANG CRITICAL	1.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
STRUCTURAL RESONANCE CASTING	1.0	0.1	0.0	0.7	0.1	0.0	0.1	0.0	0.0	0.0	0.0
PRESSURE PULSATIONS	0.8	0	0	0	0	0	0	0	0	0	0
ELECTRICALLY EXCITED VIBRATION	0.8	0	0	0	0	0	0	0	0	0	0
VIBRATION TRANSIMIT.	0.9	0.9	0	0	0	0	0	0	0	0.4	0
OIL SEAL INDUCED VIBRATION	0.9	0.7	0	0	0	0	0	0	0	0	0

Table 5.2 : Monitoring Parameter Predominant Frequencies

CAUSES OF VIBRATION ↓	SYMPTOMS →	VERTICAL	HORIZ.	AXIAL
UNBALANCE		0.4	0.5	0.1
PERMANENT BOW		0.4	0.5	0 1
TEMPORARY BOW		0 4	0.5	0.1
CASING DISTORTION		0.4	0.5	0.1
FOUNDATION DIS.		0.4	0 5	0.1
LEAF CUT		0.3	0.4	0.3
ROTOR RUB		0.3	0.4	0.3
MISALIGNMENT		0.2	0.3	0.5
PIPING-LOSSES		0.2	0.3	0.5
BRG-ECCENTRICITY		0.4	0.5	0.1
BEARING DAMAGE		0.3	0.4	0.3
EXCITED-VIBRATION		0.4	0.5	0.1
UNEQUAL-STIFFNESS		0.4	0.5	0.1
THRUST-BRG-DAMAGE		0.2	0.3	0.5
LOOSE-ASSLY-ROTOR		0.4	0.5	0.1
GEAR INACCURACY		0.2	0 2	0.6
COUPLING INACCURACY		0.3	0.4	0.3
AERODYNAMIC EXCIT.		0.3	0.4	0.3
ROTOR SYSTEM CRITIC		0.4	0 5	0.1
COUPLING CRITICAL		0.2	0.4	0.4
OVERHANG CRITICAL		0.4	0 5	0.1
STRUCTURAL RESONANCE CASTING		0.4	0.5	0.1
PRESSURE PULSATIONS		0.3	0.4	0.3
ELECTRICALLY EXCITED VIBRATION		0.3	0.4	0.3
VIBRATION TRANSIMIT.		0.3	0.4	0.3
OIL SEAL INDUCED VIBRATION		0.5	0.5	0

Table 5.3 : Monitoring Parameter Direction of Predominant Amplitude

CAUSES OF VIBRATION ↓ / SYMPTOMS →	SHAFT	BRGS	CASTING	FOUNDATION	PIPING	COUPLING
UNBALANCE	0.9	0.1	0.0	0.0	0.0	0.0
PERMANENT BOW	0.9	0.1	0.0	0.0	0.0	0.0
TEMPORARY BOW	0.9	0.1	0.0	0.0	0.0	0.0
CASING DISTORTION	0.9	0.1	0.0	0.0	0.0	0.0
FOUNDATION DIS.	0.3	0.4	0.0	0.0	0.4	0.0
LEAF CUT	0.6	0.2	0.1	0.0	0.0	0.1
ROTOR RUB	0.7	0.1	0.2	0.0	0.0	0.0
MISALIGNMENT	0.3	0.1	0.1	0.0	0.0	0.5
PIPING-LOSSES	0.3	0.1	0.1	0.0	0.0	0.5
BRG-ECCENTRICITY	0.9	0.1	0.0	0.0	0.0	0.0
BEARING DAMAGE	0.7	0.2	0.1	0.0	0.0	0.0
EXCITED-VIBRATION	0.5	0.2	0.2	0.1	0.0	0.0
UNEQUAL-STIFFNESS	0.4	0.3	0.3	0.0	0.0	0.0
THRUST-BRG-DAMAGE	0.3	0.2	0.2	0.0	0.0	0.3
LOOSE-ASSLY-ROTOR	0.6	0.2	0.1	0	0	0.1
GEAR INACCURACY	0.2	0.2	0.3	0.0	0.0	0.3
COUPLING INACCURACY	0.7	0.2	0.0	0.0	0.0	0.1
AERODYNAMIC EXCIT.	0.4	0.2	0.2	0.1	0.1	0.0
ROTOR SYSTEM CRITIC	0.7	0.3	0.0	0.0	0.0	0.0
COUPLING CRITICAL	0.1	0.1	0.0	0.0	0.0	0.8
OVERHANG CRITICAL	0.7	0.1	0.0	0.0	0.0	0.2
STRUCTURAL RESONANCE CASTING	0.0	0.4	0.4	0.1	0.1	0.0
PRESSURE PULSATIONS	0	0	0.3	0.3	0.4	0
ELECTRICALLY EXCITED VIBRATION	0	0	0.3	0.3	0.4	0
VIBRATION TRANSIMIT.	0	0	0.4	0.4	0.2	0
OIL SEAL INDUCED VIBRATION	1	0	0	0	0	0

Table 5.4 : Monitoring Parameter Location of Predominant Amplitude

CAUSES OF VIBRATION ↓	SYMPTOMS →	SAME	INCREASE	DECREASE	PEAKS	SUDDEN COME	SUDDEN DROP
UNBALANCE		0	1	0	0	0	0
PERMANENT BOW		0	1	0	0	0	0
TEMPORARY BOW		0.9	0.6	0.05	0	0.05	0
CASING DISTORTION		0.9	0.5	0.05	0	0.05	0.1
FOUNDATION DIS.		0.2	0.8	0	0	0	0
LEAF CUT		0.1	0 7	0	0	0.1	0 1
ROTOR RUB		0.1	0.4	0.1	0	0.2	0.2
MISALIGNMENT		0.2	0.9	0.1	0	0.2	0.2
PIPING-LOSSES		0.2	0.4	0	0	0.2	0.2
BRG-ECCENTRICITY		0.4	0.5	0.1	0	0	0
BEARING DAMAGE		0.1	0.5	0.1	0	0.2	0.1
EXCITED-VIBRATION		0.0	0.1	0	0	0.2	0.0
UNEQUAL-STIFFNESS		0.0	0.4	0	0.5	0.1	0.0
THRUST-BRG-DAMAGE		0.2	0.5	0.1	0	0.1	0.1
LOOSE-ASSLY-ROTOR		0	0	0	0	0.2	0.1
GEAR INACCURACY		0.2	0.2	0.2	0.2	0.1	0.1
COUPLING INACCURACY		0.1	0.2	0	0.4	0.1	0
AERODYNAMIC EXCIT.		0.2	0.2	0.2	0	0.9	0.1
ROTOR SYSTEM CRITIC		0.0	0.2	0.0	0.8	0.0	0.0
COUPLING CRITICAL		0.0	0.2	0.0	0.8	0.0	0.0
OVERHANG CRITICAL		0.0	0.9	0 0	0.7	0.0	0.0
STRUCTURAL RESONANCE CASTING		0.0	0.2	0.0	0.8	0.0	0.0
PRESSURE PULSATIONS		0.2	0.02	0.02	0.02	0.02	0.02
ELECTRICALLY EXCITED VIBRATION		0.2	0.02	0.02	0.02	0.02	0.02
VIBRATION TRANSIMIT.		0.2	0.02	0.02	0.02	0.02	0.02
OIL SEAL INDUCED VIBRATION		0	0.9	0	0	0.7	0

Table 5.5 : Amplitude Response to Speed Variation During Vibration-Test

Speed Coming Up

CAUSES OF VIBRATION ↓	SYMPTOMS →	SAME	INCRE-ASES	DECREA-SES	SUDDENLY COMES	DROPS SUDDENLY
UNBALANCE		0	0	1	0	0
PERMANENT BOW		0	0	1	0	0
TEMPORARY BOW		0.3	0 05	0.5	0.05	0.1
CASING DISTORTION		0 9	0.05	0.5	0 05	0.1
FOUNDATION DIS.		0 2	0	0 8	0	0
LEAF CUT		0.1	0	0 7	0.1	0.1
ROTOR RUB		0.1	0	0.5	0 2	0.2
MISALIGNMENT		0.2	0	0.4	0 2	0.2
PIPING-LOSSES		0 2	0	0.4	0.2	0.2
BRG-ECCENTRICITY		0.4	0.1	0.5	0	0
BEARING DAMAGE		0 1	0.1	0.5	0 1	0.2
EXCITED-VIBRATION		0.0	0.0	0.1	0.0	0.9
UNEQUAL-STIFFNESS		0.0	0.0	0.4	0.0	0.6
THRUST-BRG-DAMAGE		0.2	0 1	0.5	0 1	0.1
LOOSE-ASSLY-ROTOR		0	0	0	0.1	0.9
GEAR INACCURACY		0.2	0.2	0.2	0.1	0.1
COUPLING INACCURACY		0 1	0.0	0.2	0.1	0.4
AERODYNAMIC EXCIT.		0 2	0.2	0.2	0.1	0.3
ROTOR SYSTEM CRITIC		0.0	0.0	0.2	0.0	0.0
COUPLING CRITICAL		0.0	0.0	0.2	0.5	0.0
OVERHANG CRITICAL		0.0	0.0	0.3	0.0	0.0
STRUCTURAL RESONANCE CASTING		0.0	0.0	0.2	0.0	0.0
PRESSURE PULSATIONS		0.9	0.03	0.03	0.02	0.02
ELECTRICALLY EXCITED VIBRATION		0.9	0.03	0.03	0.02	0.02
VIBRATION TRANSIMIT.		0.9	0.03	0.03	0.02	0.02
OIL SEAL INDUCED VIBRATION		0	0	0.5	0	0.5

Table 5.6 : Monitoring Parameter Amplitude Response to Speed Variatio

During Vibration Test Run : Speed Slowing Down

CAUSES OF VIBRATION ↓	SYMPTOMS →	LOW FREQ. RUMBLE	LOUD. ROAR	HUM	BEAT	HIGH PITCH WHINE	SCREAM	SQUEAL	ULTRA. SONIC
UNBALANCE		0.0	0.8	0.2	0.0	0.0	0.0	0.0	0.0
PERMANENT BOW		0.0	0.8	0.2	0.0	0.0	0.0	0.0	0.0
TEMPORARY BOW		0.1	0.7	0.1	0.1	0.0	0.0	0.0	0.0
CASING DISTORTION		0.1	0.7	0.1	0.1	0.0	0.0	0.0	0.0
FOUNDATION DIS.		0.1	0.5	0.9	0.1	0.0	0.0	0.0	0.0
LEAF CUT		0.2	0.4	0.0	0.1	0.0	0.1	0.1	0.1
ROTOR RUB		0.9	0.4	0.0	0.2	0.0	0.0	0.0	0.1
MISALIGNMENT		0.0	0.4	0.4	0.2	0.0	0.0	0.0	0.0
PIPING-LOSSES		0.9	0.4	0.9	0.0	0.0	0.0	0.0	0.0
BRG-ECCENTRICITY		0.0	0.1	0.9	0.0	0.0	0.0	0.0	0.0
BEARING DAMAGE		0.2	0.4	0.1	0.0	0.1	0.1	0.1	0.0
EXCITED-VIBRATION		0.6	0.1	0.0	0.9	0.0	0.0	0.0	0.0
UNEQUAL-STIFFNESS		0.0	0.1	0.6	0.2	0.1	0.0	0.0	0.0
THRUST-BRG-DAMAGE		0.8	0.1	0.1	0.0	0.0	0.0	0.0	0.0
LOOSE-ASSLY-ROTOR		0.6	0.2	0	0.2	0	0	0	0
GEAR INACCURACY		0.2	0.1	0.1	0.2	0.2	0.1	0.0	0.1
COUPLING INACCURACY		0.1	0.0	0.4	0.1	0.4	0.0	0.0	0.0
AERODYNAMIC EXCIT.		0.4	0.0	0.0	0.6	0.0	0.0	0.0	0.0
ROTOR SYSTEM CRITIC		0.0	0.5	0.9	0.2	0.0	0.0	0.0	0.0
COUPLING CRITICAL		0.0	0.2	0.4	0.2	0.2	0.0	0.0	0.0
OVERHANG CRITICAL		0.0	0.5	0.4	0.1	0.0	0.0	0.0	0.0
STRUCTURAL RESONANCE CASTING		0.2	0.0	0.2	0.6	0.0	0.0	0.0	0.0
PRESSURE PULSATIONS		0.4	0.2	0	0.4	0	0	0	0
ELECTRICALLY EXCITED VIBRATION		0	0.1	0.8	0.1	0	0	0	0
VIBRATION TRANSMIT.		0.2	0	0.2	0.6	0	0	0	0
OIL SEAL INDUCED VIBRATION		0.9	0.4	0	0	0	0	0	0

Table 5.7 : Monitoring Parameter Predominanat Sound (During Vibration Test Run)

CAUSES OF VIBRATION ↓ / SYMPTOMS →	SEALS RUBBED	SHAFT BENT	THRUST BEARING DAMAUE	BEARING FAILED			CASE DISTORT/ CRACKED	OUT OF ALIGN. MENT	COUPLING BURNT/ PITTED	GEAR TEETH BROKEN/ PITTED	GEAR TEETH MARKED ON BACK	SHAFT CRACK/ BREAK
				WIPED	FATIGUED	BABBIT SQUEZED						
UNBALANCE	0.1	0	0	0.1	0.1	0	0	0	0	0	0	0
PERMANENT BOW	0.5	0	0	0.3	0.1	0.1	0	0	0	0	0	0
TEMPORARY BOW	0.9	0.1	0	0.5	0	0.2	0	0	0.2	0.2	0.2	0.05
CASING DISTORTION	0.9	0.1	0	0.5	0.1	0.1	0	0.1	0.2	0	0	0
FOUNDATION DIS.	0.9	0.1	0	0.5	0.3	0	0	0.5	0.3	0	0	0
LEAF CUT	0	0.15	0	0.15	0.1	0.1	0.1	0.2	0.1	0	0	0
ROTOR RUB	0.9	0.3	0.9	0.5	0	0	0	0	0.2	0	0	0.1
MISALIGNMENT	0.5	0.1	0.8	0.1	0.2	0	0.2	0	0.4	0	0	0
PIPING-LOSSES	0.5	0.1	0	0.1	0.2	0	0.4	0.4	0.4	0	0	0
BRG-ECCENTRICITY	0	0	0	0.1	0.6	0	0	0	0	0	0	0
BEARING DAMAGE	0.9	0.1	0	0	0	0	0.1	0.4	0.2	0.2	0.1	0.1
EXCITED-VIBRATION	0.9	0.1	0	0.8	0.6	0.3	0	0	0.2	0.2	0.1	0.1
UNEQUAL-STIFFNESS	0.1	0	0	0.4	0.4	0	0	0	0	0	0	0
THRUST-BRG-DAMAGE	0.2	0.2	0	0.5	0	0.2	0	0	0	0	0	0.1
LOOSE-ASSLY-ROTOR	0.9	0.1	0	0.6	0.3	0.4	0	0	0.8	0.4	0.4	0.2
GEAR INACCURACY	0	0	0.4	0.1	0.2	0	0	0	0	0.4	0.2	0.1
COUPLING INACCURACY	0.2	0	0.3	0.1	0.2	0	0	0	0.4	0	0	0
AERODYNAMIC EXCIT	0.1	0	0.5	0.2	0.3	0	0	0	0.3	0.2	0.2	0.05
ROTOR SYSTEM CRITIC	0.5	0.1	0	0.5	0.5	0	0	0	0.3	0.2	0.1	0.05
COUPLING CRITICAL	0.3	0.1	0	0.5	0.5	0	0	0	0.3	0	0	0
OVERHANG CRITICAL	0.5	0.2	0	0.6	0.6	0.1	0	0	0.4	0	0	0.05
STRUCTURAL RESONANCE CASTING	0.2	0	0	0.2	0.2	0	0	0	0	0	0	0
PRESSURE PULSATIONS	0.3	0	0.9	0.3	0.9	0	0	0.2	0.3	0	0	0
ELECTRICALLY EXCITED VIBRATION	0	0	0	0.2	0.2	0	0	0	0.9	0.1	0.1	0.05
VIBRATION TRANSMIT	0.2	0	0	0.2	0.2	0	0	0	0	0	0	0
OIL SEAL INDUCED VIBRATION	0.9	0.5	0	0	0.9	0.1	0.2	0	0.5	0	0	0.1

Table 5.8a : Monitoring Parameter Known Operational Evidence

CAUSES OF VIBRATION ↓ / SYMPTOMS →	[illegible]	COUPL[illegible]	FOUNDAT[illegible] CRACKED	SOLE[illegible]	SL[illegible]	THERMAL[illegible]	FLUI[illegible] ON	ROTOR[illegible]	[illegible]	SALT DEPOSIT INTERNAL	MAIN[illegible]	SEALS [illegible]
UNBALANCE	0	0	0	0	0	0	0	0	0.2	0.2	0	0
PERMANENT BOW	0	0	0	0	0	0	0.2	0.2	0.6	0.6	0	0.1
TEMPORARY BOW	0	0.05	0	0	0	0	0	0	0	0	0	0.2
CASING DISTORTION	0	0	0	0	0.9	0.3	0	0	0	0	0.5	0.2
FOUNDATION DIS.	0	0	0	0.3	0.3	0.1	0	0	0	0	0.2	0.1
LEAF CUT	0	0	0.1	0.1	0.1	0.1	0.1	0	0.1	0.1	0	0.5
ROTOR RUB	0	0.1	0	0	0.2	0.4	0	0	0	0	0	0.5
MISALIGNMENT	0	0.1	0.5	0.5	0.1	0.5	0	0	0	0	0	0.1
PIPING-LOSSES	0	0.1	0	0.1	0.2	0.5	0	0	0	0	0.5	0.1
BRG-ECCENTRICITY	0	0	0	0	0	0	0	0	0	0	0	0
BEARING DAMAGE	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.1	0.1	0.1	0.1	0.1
EXCITED-VIBRATION	0.1	0	0	0	0	0	0	0	0	0	0	0.1
UNEQUAL-STIFFNESS	0	0	0	0	0	0	0	0	0	0	0	0.1
THRUST-BRG-DAMAGE	0	0.1	0	0	0	0	0.5	0.3	0.6	0.6	0	0.5
LOOSE-ASSLY-ROTOR	0.5	0.1	0	0	0	0	0.4	0.1	0	0	0	0.3
GEAR INACCURACY	0	0	0	0	0	0	0	0	0	0	0	0
COUPLING INACCURACY	0	0	0	0	0	0	0	0	0	0	0	0.1
AERODYNAMIC EXCIT.	0.2	0.1	0.1	0.3	0	0	0	0.4	0.4	0	0	0.2
ROTOR SYSTEM CRITIC	0	0	0	0	0	0	0	0	0	0	0	0.2
COUPLING CRITICAL	0	0	0	0	0	0	0	0	0	0	0	0
OVERHANG CRITICAL	0	0	0	0	0	0	0	0	0	0	0	0.25
STRUCTURAL RESONANCE CASTING	0	0	0	0	0	0	0	0	0	0	0	0.1
PRESSURE PULSATIONS	0	0	0.3	0.2	0	0	0	0	0	0	0	0.15
ELECTRICALLY EXCITED VIBRATION	0	0.05	0	0	0	0	0	0	0	0	0	0
VIBRATION TRANSIMIT.	0	0	0	0	0	0	0	0	0	0	0	0.1
OIL SEAL INDUCED VIBRATION	0	0.2	0.4	0.4	0	0	0	0	0	0	0	0.2

Table 5.8b : Monitoring Parameter Known Operational Evidence

'Car' and 'cdr' operations are done to feed / alter elements of the list.

5.2 User Inerface

User interface is provided to feed in the observation on the machine under diagnosis. On execution the shell progresses frame by frame and puts forth a set of questions to the user for his / her responses. A typical question-answer session with the user is described below.

(The output of the program is given in 'standard font' below while the user responses are in the *italics* font. Explanation is starred (*).)

```
WELCOME TO THE PROGRAM FOR DETERMINATION
      OF FAULTS IN ROTATING MACHINERY
```

SCREEN 1

```
              SELECT THE LOGIC ANALYZER
Do  you want to  use  the  BAYE's method   (Type 1)
Do  you want to use the MVIM method        (Type 2)
    Type any other key to exit
          ................ 1
```

SCREEN 2

Please answer the following in yes / no only .

If you chance to feed in incorrectly somewhere then carry on, you can correct in the end.

SCREEN 3

FRAME FOR PREDOMINANT FREQUENCIES

Is the predominant frequency equal to rotor or stator resonant frequency ?...No

Is it equal to 40 - 50 % oil whirl frequency ?...No

Is it equal to 50 - 100 % oil whirl frequency ?...No

Is it equal to running frequency ?...Yes

Is it equal twice running frequency ?...No

Is it a higher multiple of running frequency ?...No

Is it half of running frequency ?...No

Is it quarter of running frequency ?...No

Is it a lower multiple of running frequency ?...No

Is it an odd frequency ?...No

Is it a very high frequency ?...No

SCEARREN 4

FRAME FOR THE DIRECTION OF PREDOMINANT AMPLITUDE

Is the direction vertical ?...No

Is the direction horizontal ?...Yes

Is the direction axial ?...No

SCREEN 5

FRAME FOR THE LOCATION OF PREDOMINANT AMPLITUDE

Is it in the shaft ?...*Yes*

Is it in the bearings ?...*No*

Is it in the casting ?...*No*

Is it in the foundation ?...*No*

Is it in the piping ?...*No*

Is it in the coupling ?...*No*

SCREEN 6

FRAME FOR AMPLITUDE RESPONSE TO SPEED VARIATION (COMING UP)

Does it stay same ?...*No*

Does it increase ?...*Yes*

Does it decrease ?...*No*

Does it peak ?...*No*

Does it come suddenly ?...*No*

Does it drop out suddenly ?...*No*

SCREEN 7

FRAME FOR AMPLITUDE RESPONSE TO SPEED VARIATION
(SLOWING DOWN)

Does it stay same ?...*No*

Does it increase ?...*No*

Does it decrease ?...*Yes*

Does it come suddenly ?...*No*

Does it drop out suddenly ?...*No*

SCREEN 8

FRAME FOR PREDOMINANT SOUND
(DURING VIBRATION TEST RUN)

Is the predominant sound a low frequency rumble ?...*No*

Is it a loud roar ?...*Yes*

Is it a hum ?...No

Is it a beat ? (i e Does it come and go periodically ?)...*No*

Is it a high pitched whine ?...*No*

Is it a very high loud scream ?...*No*

Is it a very high squeal ?...*No*

Is it ultrasonic (measured with sound analyzer) ?...*No*

SCREEN 9

FRAME FOR RESPONSES FOR THE EFFECT OF OPERATING CONDITIONS

COMES IN OR GOES OUT AT

No effect ?...*Yes*

Full load in ?...*No*

Full load out ?...*No*

No load in ?...*No*

No load out ?...*No*

Part load in ?...*No*

Part load out ?...*No*

Start up only ?...*No*

After load dump or surge ?...*No*

When other machine starts or shuts down ?...*No*

SCREEN 10

FRAME FOR KNOWN OPERATIONAL EVIDENCE

Are the seals rubbed ?...*Yes*

Is the shaft bent ?...*No*

Is the thrust bearing damaged ?...*No*

Have the bearings wiped out ?...*No*

Have the bearings fatigued ?...*No*

Have the bearings babbit squeezed out ?...*No*

Has the case distorted or cracked ?...*No*

Is there misalignment ?...*No*

Is the coupling burned or pitted ?...*No*

SCREEN 11

FRAME FOR KNOWN OPERATIONAL EVIDENCE

Are the gear teeth broken or pitted ?...No

Are the gear teeth marked on the back side?...No

Is the shaft cracked or broken ?...No

Are there gailing or fretting marks under disks or hubs ?...No

Are the coupling bolts loose ?...No

Is the foundation cracked ?...No

Is the soleplate loose or rusted ?...No

Are the sliding surfaces binding ?...No

Is thermal expansion restricted ?...No

Are there fluid marks on the internals ?...No

Are the rotor components eroded ?...No

Has solid accumulated on vanes and rotor ?...Yes

Has salt deposited on internals ?...Yes

Are main flanges leaking ?...No

Are the seals leaking ?...No

SCREEN 11

FRAME FOR THE HISTORY OF MACHINE

Has the machine had initial start-up ?...Yes

Has it had start-up during the first year ?...No

Has it had start-up after one year but before ten years ?...No

Has it had start-up after ten years ?...No

SCREEN 12

DATA MODIFICATION

Do you want to feed again in the set of responses for any symptom (yes or no) ?....*No*

* *(If user had printed yes following would have been printed on the screen*

Write -

1 - If you want to to refeed for predominant amplitude

2 - For direction of predominant amplitude

3 - For its Location

4 - For Amplitude Response - Speed Coming up

5 - For Amplitude Response - Speed Slowing down

6 - For Predominant Sound (During vibration test run)

7 - For Effect of Operating Conditions

8 - For Known Operational Evidence

9 - For History of Machine

....

)

SCREEN 13

5.3 Shell Output

The shell output comprises of the list of the top seven defects in the order of decreasing probability.

```
DIAGNOSIS

(Permanent-Bow    0.99911)

(Unbalance    0.99369)

(Bearing-Damage    0.0.00183)

(Temporary-Bow  0.0)

(Casing-distortion  0.0)

(Foundation-Distortion  0.0)

(Seal-Rub  0.0)
```

SCREEN 14

```
Do you want to know the MVIM method answer also.
If yes type yes else type any other key to exit....Yes
```

SCREEN 15

```
DIAGNOSIS

(Permanent-Bow  0.9055)

(Unbalance    0.8756)

(Temporary-Bow  0.733)

(Bearing-Damage    0.7208)

(Foundation-Distortion    0.6414)

(Overhang-Critical  0.272)

(Leaf-cut  0.62)
```

SCREEN 16

5.4 Comments

The shell is developed in such a way that additional fault and symptom-set can be added without much modifications . By changing the set of causes and the set of symptoms the program can also be extended to any case where two parameters are related by cause-effect relationship.

CHAPTER 6

CONCLUSION

A software shell has been developed and illustrated for diagnosis of faults in rotating machinery installations. Techniques of expert system programming have been employed for the development of the shell.

The shell comprises of a Knowledge Base in the form of Frames, a Probabilistic logic Analyzer and a Network. Two different engines, one based on Baye's Method for probabilistic reasoning and the other based on Influence Matrix Approach are constructed for inferencing. The shell is illustrated for set Knowledge-Base for the case of a High Speed Turbomachine in a Petroleum Plant.

Though the shell is developed with the view of specific application to rotating machinery, minor modifications may permit the usage of the shell to more general classes of machinery. The User Interface can be refined to give the user to define his/her own set of Monitoring parameters and therefore the Knowledge Frames. The Causes and symptoms can be defined through the user-interface. Interface can be further can be further modified to allow for on-screen creation of knowledge base by the user.

Feasibilities studies on the usage of the shell to cases like medical diagnosis and weather forecasting can also be undertaken.

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